Transducers For Instrumentation

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Lecture - 17

Optical Sensors: PIN photo Detectors

Hello, welcome to the course Transducers for Instrumentation. Last lecture we were discussing about ah the photo detectors ah these are semi semiconductor devices and before discussing the photo detectors, we were discussing some of the device physics which is involved in fabricating and understanding the functionality of these photo detectors. So, we discussed earlier that ah based on the band gap of a material, we can classify them into ah three kinds of material, one is metal, then we have a insulators and then we have semiconductors where the band gap is not that high ah like a insulator or it is not even overlapping just like metal. So, we have a decent band gap between conduction band and valence band and based on that we can classify these semiconductors. These semiconductors then we discussed the energy bands, we have at temperature T equal to 0, we do not have any mobile electrons present in conduction band. So, there is no kind of conduction in semiconductors for ah time for temperature T equal to 0, but when we increase the temperature electrons acquire enough energy to move to the conduction band and then they can contribute to conduction.

Then we discussed about the effective mass of a charged particle which actually depends upon the shape of band gap. So, the how the band is actually the shape of this band gap dictates how much will be the effective mass of that charged particle in that particular energy band. So, let us discuss that energy band ah let us derive how the energy band shape dictates the effective mass of a charged particle. So, the particle effective mass let us derive the formula for this. So, let us say we have a E K diagram or the energy momentum diagram, this axis is E axis and this is K or E the momentum and we have a certain band something like this, let us assume that this is parabolic. So, for this band we can write the energy of the charged particle E is equal to half m naught into V square. This is the kinetic energy of this charged particle m naught is the effective mass and V is the velocity. This I can write like E square upon 2 m where this E is the momentum which is which can be written h into K or this E square upon 2 m I can write h square K square divided by 2 m naught m naught is h h is the plant constant here. So, I can write del E by del K the derivative of energy with respect to K is twice h square K divided by m naught or h into P divided by m naught or I can write even h into m naught V power m naught.

Now the velocity I can write 1 over h into del E by del K. So, here we can see del E by del K is the derivative of this band with respect to K. So, del E by del K is nothing, but the slope of this graph of this band with respect to K. So, I can write now here del square

E by del K square the second derivative of this band with respect to K is nothing, but del by del K of h square K divided by m naught or it comes out h square upon m naught or I can again rearrange it the mass or I would say the effective mass m naught of this we have 1 over h square into del square E by del K square. So, this is the relation of effective mass with respect to the shape or the second derivative of this E K diagram. So, here we can see the effective mass m naught is inversely proportional to the curvature of this band. So, here this is 1 over m naught in fact, 1 over m naught is equal to half 1 over K square d square E over d K square. So, we can see the m naught which is the effective mass is inversely proportional to del square E by del K square which is actually the second derivative of this E K diagram or the or the this band. The second derivative means the curvature how fast this slope is changing with respect to K. So, it means the more the curvature of this band actually dictates how much will be the effective mass of a particular charge carrier.

This does not depend on it is not a fixed value it changes the mass of this charged particle it changes where this a charged particle is in that particular band. So, if a band is kind of flat the mass will be different if the band is very sharp the mass of that same charged particle will be different. So, this is the relation which is we can write in the text. The second derivative of E versus K is inversely proportional to the effective mass of free electrons. So, the mass of a charged particle is inversely proportional to the curvature or the second derivative of the band with respect to K. Now, based on the band gap how the band are located in a particular material we can classify these materials in two types one is the direct band gap semiconductor and one is the indirect band gap semiconductor. And we will see that why for optical devices to make a optical detector optical sources why do we need a direct band gap material compared to an indirect band gap material. So, we have two types of materials based on the band gaps we have direct and indirect band gap materials. So, let us first discuss a direct band gap material we plot E versus K this is etcetera and we have P like this and the bands are something like this. This is the balance band and we have the conduction band which looks something like this is the conduction band this is the band gap. Band gap is the difference in the energy of these two bands at the maximum of balance band and the conduct the minimum of conduction band. So, we have some charged particle let us say we say these are the charged particles here and here and there are some charged particles in the conduction band this is direct band. So, here if we see we see a conduction band where there is a minima and we see a balance band where there is a maximum and both of these minima and maxima they exist at the same value of K at the same value of momentum axis. It means these electrons which are there this black these black electrons we have in conduction band and balance band. These electrons can jump to for example, from balance band to conduction band just by acquiring certain amount of energy they can acquire some energy from external means and they jump from conduction to balance to conduction or conduction to balance and in this process they need not to change their momentum because the momentum is same for both minima and maximum. So, they can easily jump from balance to conduction and conduction to balance. So, to jump from balance to conduction it means go up they just acquire some energy and they can jump up in the reverse process they can jump from conduction to balance and they can emit a photon they have to lose this amount of energy the equivalent to E g the band gap they need to lose this much of energy to jump from conduction to balance and this energy will be released in terms of photon and the energy of that photon will be equal to the band gap of material which is E g in this case. So, in this process we see the electron or the charge carrier they need not to change their momentum it is a easy process just is the losing or acquiring some energy in terms of photons. So, this process is easy or I would say efficient to jump from up and down from one band to another this is called direct band gap material. So, this kind of material is used for optical devices because they need not to change their momentum it is a efficient process the material l can easily absorb the photon or it can easily emit the photon.

So, this is a direct band gap material which is used for optical devices the other case is the indirect band gap material which we will discuss now. So, in indirect band gap material we have this k axis and we have this E axis and the band look like something this is the valence band and the conduction band look something like this. So, here if we see this conduction band minima this is the minima point this does not exist for the same value of k where the maximum of valence band is. So, we have electrons in the valence band which exist here and in the minima of conduction band the electrons exist here and we have the band gap which is Eg which is the difference between the maxima and the minima this value. So, here if we see we have a conduction band where the minima is at different k value than the maxima of valence band means this electron which is in the valence band if it has to jump to conduction band it has to do two process in that jumping from valence to conduction the first is it has to acquire certain amount of energy equivalent to the Eg the band gap.

So, that it can jump that much of energy barrier and it has to change its momentum the momentum is kind of E is equal M into V it has to change its momentum to jump from valence to conduction. So, it has to do two process and the same it is a kind of in the reverse process when it jump to conduction to valence it has to lose certain amount of energy it has to lose that photon with equivalent to some band gap and it has to change its momentum which is a physical quantity we call it the phonon. So, one is the photon and one is the phonon. So, photon is the amount of energy which is released as a optic as a kind of optical energy in terms of photon and phonon is the amount of energy which is acquired or given to the lattice. So, here if we see the conduction band this electron now if it has to jump from this conduction to valence first it has to change its momentum and come to the same momentum point.

So, this electron first it goes to the same value by releasing a phonon here this emits a phonon and then jumping from this place to the valence band it emits a photon. The phonon is something it change its momentum and release this energy to the lattice and when it energy is burnt in the lattice the lattice heats up. So, this process of releasing a photon is not as efficient or as good compared to the direct band gap materials. So, we call this as indirect band gap semiconductor this process of releasing a photon is not that efficient. So, we do not use this kind of material in making optical devices.

So, silicon is one example of this indirect band gap material where silicon if we bias it does not in fact, efficiently emit photon, but it release phonon phonon releasing a phonon means the energy is released to the lattice it means the device heats up. The lattice of the material starts acquiring this energy from those biases and phonons will be generated instead of photons. So, silicon will not be as effective or it is not usable for optical devices. So, these materials are indirect band gap materials. Indirect band gap materials and these direct band gap materials are good for optical devices.

So, now let us discuss about the photo detectors and how do we make these photo detector devices these are made of semiconductor devices which actually receives a photon and gives its response as the electrical signal. So, photo detector is a device which converts optical signal into electrical signal. And this is the fundamental element of optical receivers. So, these photo detectors are the device which converts the optical energy which is photon, and it converts it in equivalent electrical signal which is current or voltage. So, these devices when we employ these kind of device in circuitry most of the time these devices are followed by some amplifier because the output generated by these optical devices these are very small in magnitude because the photon receive and converted into the electrical electrical output those numbers are small.

So, these optical receivers or the optical devices these are followed by an amplifier and that amplifier is again followed by some single signal conditioning how do we process this data. So, some of the requirements of these photo detectors are like we have some requirement for these. The first one is they should be smaller in size. We can write compatible physical dimensions means they should be small in size. The second one is low noise and high gain.

The third is the fast response. It means they should have a high bandwidth. The fourth is insensitive to temperature variation. And the fifth one is long operating life and low cost. So, we have certain requirements from these optical detectors. First is the compatible physical dimensions and should be small size because we need to couple these devices with the optical fibers and optical fibers are very the diameter of these optical fibers are very small these are very thin strands. So, the smaller size of these optical detector is good for the operation. The second is the low noise and high gain. So, the device should not generate much of a noise and the gain of these devices should be high. So, that we can detect even a small amount of photon as well. So, that the gain of these devices should be high. The third is the fast response time because the if we can have a fast response time means that we can have a very high bandwidth and we can we can transfer the signal at much higher rate. So, we should have a fast response time. The fourth is insensitive to temperature variation which is in fact, a requirement for almost all the sensors we have. And the fifth one is the long operating life and low cost because the fabrication of these devices are very expensive. So, the fabrication cost of these devices should be should be should we should bring it to lower value. So, that we can deploy them in a large number of devices. So, we can have now photo detectors. And in these photo detectors in fact, the photo diodes meet most of the requirements. Hence, widely used as photo detectors. So, we use photo diodes as photo detectors because they meet most of the requirements and there are two types of photo diodes we use. The first one is the PIN photo diode or we can say the positive intrinsic negative or in short we call it PIN. So, the these are type of photo diodes where we have no internal gain and robust these are robust detectors. And the second one is the avalanche photo diode. Or in short we call it APD avalanche photo diode.

In this we have it is an advanced version of this PIN where we can have with internal gain. Let us say M this is due to the cell multiplication process. So, we have two types of photo detectors or the photo diodes. One is the PIN photo diode where this diode does not have any internal gain. It means one photon is received then one amount of electrical signal will be generated. And the other is the avalanche photo diode this photo diode has internal gain. So, if a one photon is received it multiplies the response within itself. So, that we can get M times the response of what a single photon can generate. So, these are two types one is PIN the the name itself confirm the structure positive intrinsic and negative which which we going to discuss next. And the second is the avalanche photo diode where we have the internal gain. Most of both of these devices need to be biased in the reverse bias. We apply a high electric field across these devices in the reverse bias case. So, we have these photo diodes are sufficiently reversed biased during normal operation means no current flow without illumination. And the intrinsic region is fully depleted of cables. So, these photo diodes are always sufficiently reversed biased we apply the voltage such that this diode is always biased in the reverse bias.

And in the reverse bias we do not have a conduction a current flowing into the into the device. And the intrinsic region which is in between this this P and N type for example, positive intrinsic and negative this intrinsic layer is completely depleted of any charge carrier. So, there is no current flow in the device we always bias in the reverse bias. So, let us now let us now discuss how a P I N diode look like. This is P I N photo diode. So, the P I N photo diode look like we have a diode here and it has mainly three regions. The first one is P type this is P type dope and this is N type dope and in between we have intrinsic region. And I have purposely made it bigger because the reception of signal is going to happen in this intrinsic region only. So, this is our photo diode and we bias it in the reverse bias. So, this terminal P type we apply to negative of the battery. So, this is negative connected to P type and the positive is connected to N type. So, this whole device is connected in reverse bias and we receive signal electrical signal across these two points. We have here. So, we have here a resistance connected between these two terminals. So, across this resistance we receive electrical signal this is our load resistance R L and we receive signal across this load resistance which is our output. So, in this structure if we see we have P I N three regions of the device this photo diodes P type intrinsic and N type. So, intrinsic region is anyway depleted of charge carriers we do not have any doping in this intrinsic region. So, no charge no freely moving charge carriers here. This intrinsic region is exposed to the incoming photons. For example, we align this intrinsic region to the optical fiber which is bringing these photons or the light energy from other kind of side. These photons hit this intrinsic region and we have biased whole of this here this photo diode in reverse bias it means the whole of the electric field from the battery is applied across this intrinsic region. This intrinsic region is having a very high electric field build up because of this reverse bias applied. So, this intrinsic region which is applied to a very high electric field within itself now it is exposed to the photons the photon comes in. So, what happens let us see we receive a photon here this photon comes in here which is now being absorbed by this intrinsic region absorbed means the energy of this photon is now released to the material what this energy will do this energy will knock down electron and hole in itself which generates a electron hole pair. So, this photon here it gets annihilated and generate electron hole pair one is the negative its electron and one is photon sorry the hole.

So, it generates electron hole pair by releasing the energy to the the material and now this electron hole pair they see a high electric field across this intrinsic region. So, they move in in that electric field direction electron moves to the right and the hole moves to the left and this electron hole pair is generated when these electron hole pair complete their journey from here when they are generated and reach reach the terminal they develop a potential across this load resistance because these are charge carriers when they move the current will flow and that this current will be flowing into this load resistance which we can measure here as a output. So, the output we receive across this load resistance as electrical signal. So, this is how the current is actually generated in these photo diodes we can write it down here the high electric field present in the depletion region causes photo generated carriers to separate to be collected this gives rise to the current in the external circuit which is known as photo correct. So, we apply this reverse bias and the photon comes in release the energy and this release energy knocks down electron hole pair these electron hole pair because of the applied reverse bias they move accordingly and when this charge pair carriers move in the circuit they produce a current which is detected by our load resistance and we sense this as a output of this devices.

Now, this electrical current we see is proportional to how many photons we receive if we receive one photon only one electron hole pair is generated which gives rise to a small current if we get 100 photons. So, it means 100 electron hole pairs will be generated and it gives rise to more current. So, the same amount of current is detected by the load resistance as a output. So, if we see the band diagram of this structure. We have a conduction band and a valance band in p side. And we have a conduction band and valance band in the n side and in the intrinsic region because we apply a high electric field there is a slope of this conduction and valance band. So, this is how these conduction band and valance band look like. This is p region this is n region and this is our intrinsic region and when the electron hole pair is generated let us say we generate a electron here and a hole here they move in to opposite direction electron comes down to downward and the hole which look which act like a bubble it goes up when a photon is actually getting this position. Let us say we have a photon which is having some energy eg and the photon energy which is actually h into mu the frequency of this photon. So, here we see the photon energy should be equal or more than the band gap of this material because electron hole pair which is generated now this electron need to jump to conduction band.

So, the amount of energy which is required to knock down electron hole pair is at least equal to the band gap of the material. So, here eg is the band gap of this material what we choose on. So, different different materials use different detect different kind of light. So, for example, one material the band gap is close to the blue light it is a good detector for the blue light. However, a different material where the band gap is more close to the red light that material will be good for detection of red light. So, this is how we choose different materials to detect different colors of light. So, this is the band gap of this is the band energy band diagram of photo diode. Now, let us discuss we have some optical power some optical power is is received by this device. Now the optical power absorbed in in the depletion region. Can be written as P as a function of x is equal to P naught into 1 minus e to power minus alpha s which is a function of lambda into x. Here P naught is the incident power. And x is the distance and this alpha which is in fact a function of lambda is the absorption coefficient. So, let us assume P naught amount of energy the optical energy is incident on this material how much of the energy will be absorbed by this material this optical energy. So, when the energy falls the P naught energy falls into the material right at the interface all the energy is not absorbed by the material. Some of the energy some of the photons goes well within the material and they get absorbed at at certain distance away from the surface. So, when this energy hits the material it goes little bit into the material itself some photon goes into the material and goes and get annihilated after a certain distance which is x and the relation between this x the distance and the amount of energy absorbed is given by this P equal to P naught which is the incident energy into 1 minus e to power minus alpha into x.

This alpha is the absorption coefficient how efficiently the material absorbs this optical power or the photons. And this absorption coefficient is a material property different materials have different different absorption coefficient. And this alpha is also a function of the lambda which is the wavelength of optical energy what type of optical energy is incident on the material. So, accordingly this absorption coefficient is also different. So, this is the relation between absorbed energy and the incident energy. Next is this absorption coefficient alpha strongly depends on wavelength. And the lambda of the optical energy is given by we can write in micrometer. So, this formula directly give the value in micrometer 1.24 upon the band gap energy which is in electron volt. So, if we write the energy of the band gap energy in electron volt this formula directly give the value of lambda in micrometer. The next is if we take the reflectivity also into account. The absorbed power is given by 1 minus R f into P is equal to which is function of x is equal to P not 1 minus to power minus alpha into x into 1 minus R f. So, here when these photons are incident on the material not all the photons goes into the material because some of the part or some part of these photons will get reflected back from this material. And if we consider this reflectivity. So, let us say some portion of these photons are reflected back how much goes into the material is 1 minus the reflectivity. So, 1 minus reflectivity this is this varies from this 0 to 1. So, 1 minus R f is the amount of photons the fraction of photons which actually goes into the material and then the absorption of these photons which go inside the material they get annihilated in the intrinsic region based on this formula P x equal to P naught 1 minus e to power minus alpha into x. So, if we consider this reflectivity as well. So, we have to put the factor 1 minus R f also into account. So, the next is the photo current produced by this absorption. So, when these photons get annihilated in the intrinsic region they give rise to the photo current resulting from absorption I p the photo current is equal to Q upon h into mu into P naught 1 minus e to power minus alpha into x into 1 minus R f where this Q is the charge on an electron h is the plank constant and mu is the frequency of photon.

So, the photo current generated is I p and if let us say this has certain efficiency as well not all the photons give rise to a electron hole pair then we can have a quantum efficiency eta which is equal to number of electron hole pair generated divided by the number of incident photons or we can write it eta equal to photo current divided by Q divided by P naught the incident photon energy divided by h mu. So, this is the quantum efficiency formula and the next is the responsivity. We can write it by R is equal to I p the photo current divided by the incident optical power P naught, or we can write eta P upon h into mu. So, this is the responsivity formula where how much current is generated by P naught amount of incident photons. So, this is the responsivity and quantum efficiency is because not all the photons give rise to electron hole pair. So, how many electron hole pairs are generated or unit amount of photons incident on the material. So, that is that ratio is called the efficiency of the material how efficiently we can generate electrical signal from the optical signal. So, this is the quantum efficiency. So, today we discussed photodiodes and basically in the photodiodes we have discussed the P i n photodiode where we have P intrinsic and n type region, and this photodiode does not have any internal gain the amount of photons it receives the output electrical output is proportional to the number of photons we receive at the input.

So, this is all for today.

Thank you.